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HUMIDITY OF THE LOWER STRATOSPHERE

The Results of High-Level Ascents by Aircraft of the Meteorological Research Flight

By H. C. SHELLARD, B.Sc.

Introduction.—The results of over 70 high-level ascents made by aircraft of the Meteorological Research Flight provide data from which mean values of humidity in the upper troposphere and lower stratosphere are obtained. Mean lapse rates of frost point and temperature in the neighbourhood of the tropopause are discussed. Significant correlations are shown to exist between frost point at levels between 200 and 300 mb., height of tropopause, and temperature at 500 mb.

Available data and their treatment.—The ascents dealt with have been made at various times during the past 6 years, and include Fortress and Mosquito ascents from Boscombe Down (1943-45) as well as more recent Mosquito ascents from Farnborough, the majority of which have been made in 1949. The data consist of measurements of temperature and frost point, usually at 1,000-ft. intervals, temperatures being measured by M.O. knife-type resistance thermometers with balanced-bridge indicators, and frost points by one of the M.O. aircraft frost-point hygrometers.

The ceiling of the Mosquito aircraft employed varies between 38,000 and 41,000 ft., whilst that of the Fortress used for the ascents of 1943-44 varied from 33,000 to 37,000 ft.; nearly three-quarters of the ascents, however, reached or exceeded the 200-mb. level (38,500 ft.).

Of the 77 ascents available, ten failed to reach the tropopause, two gave doubtful results (of these more will be said later), and one consisted of such limited data that the position of the tropopause could not be fixed satisfactorily. For each of the remaining 64 ascents, the first step was to decide the tropopause height and type. It was found that the current Meteorological Office definitions as given in *S.D.T.M.* 107[1*] and in the Introduction to the *Upper Air Section of the Daily Weather Report* (the two differ slightly) were not sufficiently precise, and the following amended definitions were therefore adopted :—

*These numbers refer to the list of references on p. 349.

Type I.—There is an abrupt change of lapse rate to inversion, and for no subsequent 3,280-ft. (1-Km.) layer does the lapse rate exceed 1·1°F./1,000 ft. (2°C./Km.). H_c is the height of the abrupt change.

Type II.—There is an abrupt change to a lapse rate of less than 1·1°F/1,000 ft. (2°C./Km.), or to isothermal, and for no subsequent 3,280 ft. (1 Km.) does the lapse rate exceed 1·1°F/1,000 ft. (2°C./Km.). H_c is the height of the abrupt change.

Type III.—Where there is no abrupt change of lapse rate H_c is taken as the height of the point at which the lapse rate first becomes less than 1·1°F./1,000 ft. (2°C. /Km.), provided that it does not exceed this value for any subsequent 3,280-ft. (1-Km.) layer.

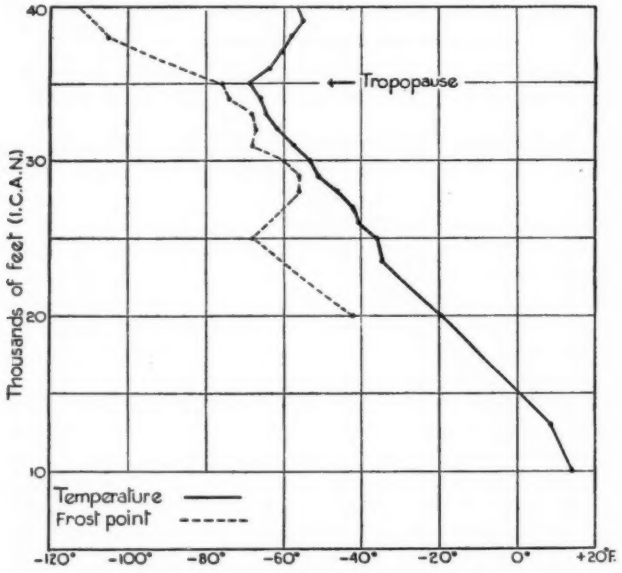

FIG. 1—AIRCRAFT SOUNDING, 1500 G.M.T., MAY 24, 1948

In addition the following rules have been adopted :—

(*a*) An abrupt change is defined as one in which the mean lapse rates measured over 1,000-ft. layers on either side of the change differ by at least 2°F./1,000 ft.

(*b*) Where there is a double tropopause, *i.e.* two abrupt changes as defined in (*a*), the lower one satisfying the Type II tropopause definition and the upper one the Type I definition given above, then in this paper the tropopause is taken as being at the lower level and is classified as Type II.

Having fixed the tropopause pressure (P_c), values of temperature and frost point were extracted from each ascent, (i) for the levels (P_c +150)mb. to (P_c −100)mb. at 25-mb. intervals, *i.e.* for levels relative to the tropopause as origin, and (ii) for the fixed pressure levels 200, 250 and 300 mb. These

values were tabulated so that means could be readily computed and values of relative humidity obtained as required. Correlation coefficients between the various quantities were also evaluated.

The mean tropopause height given by the ascents considered is about 34,000 ft., whilst that given by radio-sonde ascents for south England is about 36,000 ft. Thus there is some bias towards low tropopause in our ascents.

Discussion.—*General.*—Table I is a frequency table of relative humidity with respect to ice, which conveniently summarises the observations. The outstanding features are (i) the rapid decrease in relative humidity as the stratosphere is entered, and (ii) the fact that the relative humidity continues to decrease, though less rapidly, the further into the stratosphere one goes. Mean values are given for each level. Eight of the ascents penetrated 100 mb. into the stratosphere, the mean relative humidity at that level being 2·2 per cent. and the range 0·9 to 3·9 per cent.

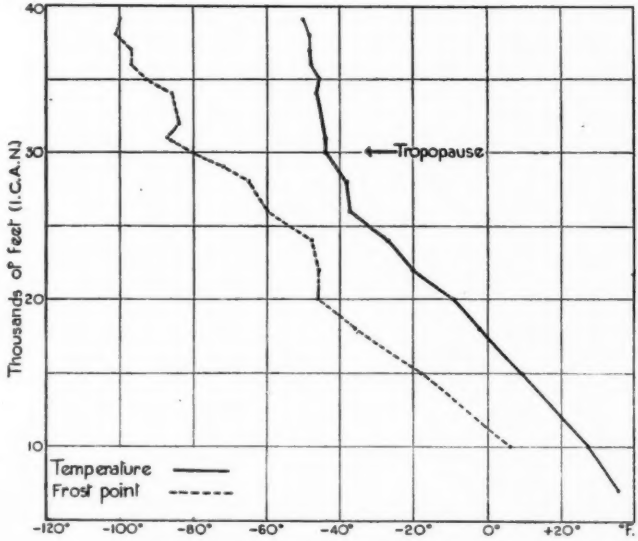

FIG. 2—AIRCRAFT SOUNDING, 0930 G.M.T., JULY 5, 1949

On examining individual ascents perhaps the first thing which strikes one is that there is often a sharp fall of frost point on entering the stratosphere. This was remarked upon by Dobson, Brewer and Cwilong[2] in their discussion of some of the early Boscombe Down ascents. This rapid fall of frost point does not always occur, however, and there are many ascents in which the frost-point lapse rate is not materially different above and below the tropopause. Typical examples of ascents of the two types are given in Figs. 1 and 2.

Further examination reveals that ascents showing this frost-point lapse discontinuity at the tropopause more often than not have Type I tropopause, whilst those showing little or no such discontinuity more often than not have Type II tropopause. On some of the first type the sharp frost-point fall does

TABLE I—FREQUENCY OF RELATIVE HUMIDITY (WITH RESPECT TO ICE)

Level \ Relative humidity range %	0–0·9	1–2·9	3–4·9	5–9·9	10–14	15–19	20–24	25–29	30–39	40–49	50–59	60–69	70–79	80–89	90–99	≥100	Mean relative humidity	Total No. of cases
50 mb. below tropopause	0	0	0	3	1	3	5	5	13	9	6	7	5	1	2	0	43·5	60
25 mb. below tropopause	0	1	0	2	5	3	4	1	12	7	11	6	3	2	2	1	44·2	60
Tropopause	0	1	1	7	3	1	4	2	14	10	6	4	6	1	3	1	42·5	64
25 mb. above tropopause	0	4	6	18	8	10	8	4	..	..	..	..	..	..	..	..	13·8	58
50 mb. above tropopause	0	16	9	7	2	2	1	..	..	..	..	..	..	..	..	..	5·3	37
75 mb. above tropopause	2	14	2	3	..	..	..	..	..	..	..	..	..	..	..	..	2·7	21
100 mb. above tropopause	1	5	2	..	..	..	..	..	..	..	..	..	..	..	..	..	2·2	8

not always coincide with the tropopause ; it may be a little higher or lower. Thus it would be impracticable to replace the existing official definitions of the tropopause, based on temperature lapse-rate changes, by a set of definitions based on frost-point lapse-rate changes.

In the stratosphere frost points nearly always lie within the range –80° to –120°F. Two exceptional ascents (mentioned earlier) made on successive days, January 19 and 20, 1948, indicated moist conditions in the stratosphere, however. The first gave a frost point of –72°F. (relative humidity 26 per cent.) and the second one of –62°F. (relative humidity 75 per cent.) at the 200-mb. level, which in each case was well into the stratosphere. For the present we have rejected these two ascents, (i) because the results are completely at variance with all others we have obtained, and (ii) because when, as in this case, observations are made with the Mk.2a hygrometer in a pressurised cabin, there is always the chance of moist cabin air leaking into the instrument. Nevertheless the possibility remains that very occasionally the air in the lower stratosphere may be nearly saturated.

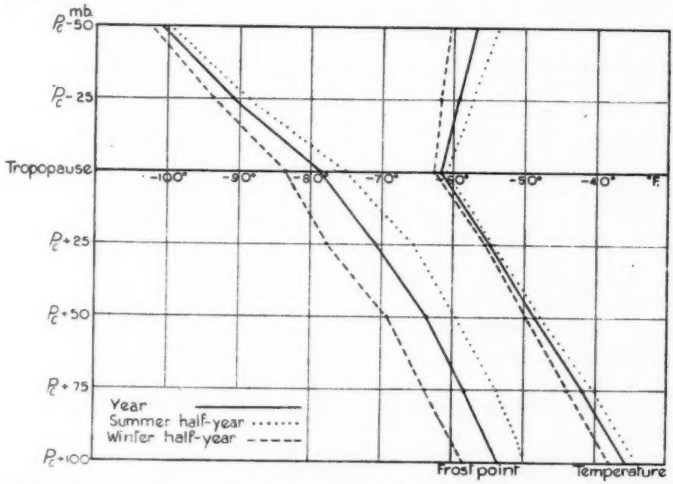

FIG. 3—MEAN CURVES FOR SELECTED ASCENTS SHOWING SEASONAL VARIATION
Year, 32 ascents, mean P_c = 272 mb.
Summer half-year, 18 ascents, mean P_c = 265 mb.
Winter half-year, 14 ascents, mean P_c = 281 mb.

Mean ascent curves.—Of our 64 ascents only 32 provide complete frost-point and temperature data between the levels (P_c +100)mb. to (P_c –50)mb., chiefly because of the limited aircraft ceiling. To obtain representative mean ascent curves penetrating the stratosphere by 50 mb. (approximately 5,000 ft. at this level), it is necessary therefore to mean the results of these 32 ascents only. Fig. 3 shows the mean curves so obtained, and also similar curves for the 14 ascents made during the winter half-year, and for the 18 ascents made during the summer half-year. Because the mean tropopause pressure over south England is at a maximum in mid February and a minimum in mid August, the winter half-year was taken as mid November to mid May and the summer half-year as mid May to mid November.

The curves of Fig. 3 indicate that there is little seasonal variation in the moisture content of the lower stratosphere. Frost points not far above the tropopause tend to be higher in summer, but further into the stratosphere the difference decreases. On the curve for the full year the average frost-point lapse is 7·9°F. in the 25-mb. layer below the tropopause. In the stratosphere the frost point falls 12·2°F. in the first and 10·0°F. in the second 25-mb. layer. The rate of fall of frost point in the stratosphere is greater than in the upper troposphere and decreases with height. It may be that the frost point in the stratosphere eventually becomes constant, though the curves of Fig. 3 do not extend sufficiently far upwards to show whether this is so or not. More ascents on occasions of low tropopause, or preferably, ascents to greater altitudes than 40,000 ft. are required.

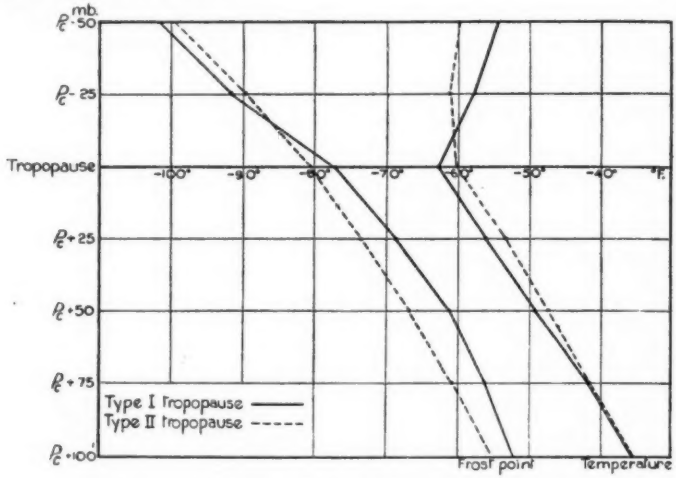

FIG. 4—MEAN CURVES FOR SELECTED ASCENTS, GROUPED ACCORDING TO TYPE OF TROPOPAUSE
Type I tropopause, 18 ascents, mean P_c = 270 mb.
Type II tropopause, 14 ascents, mean P_c = 274 mb.

Fig. 4 shows mean ascent curves for the 32 ascents when grouped according to type of tropopause. For Type I tropopause the frost point falls in the 25-mb. layer below and above the tropopause are 8·5° and 14·3°F. respectively (a difference of 5·8°F.), whilst for Type II the corresponding figures are 7·2° and 9·1°F. (a difference of only 1·9°F.). This clearly indicates the tendency for a steep frost-point lapse rate just above the tropopause to be associated with temperature inversion. On the other hand the discontinuity in frost-point lapse rate is quite small when there is no temperature inversion (Type II tropopause). It may well be that this steepening of frost-point lapse rate is not specially a characteristic of the tropopause, but that it occurs only because there is a temperature inversion, for it is well known that the same effect occurs at subsidence inversions in the troposphere.

Some correlation coefficients.—The results discussed above suggest a correlation between lapse rate of temperature and lapse rate of frost point in the lower-stratosphere. Values of temperature and of frost-point fall in the layer 25-mb.

thick above the tropopause were therefore correlated. Considering all ascents a coefficient of −0·41 from 58 pairs of values was obtained, whilst for ascents with Type I tropopause only the coefficient was −0·61 from 35 pairs of values. The probabilities of such correlations arising by random sampling from an uncorrelated population are in both cases less than one in one hundred.

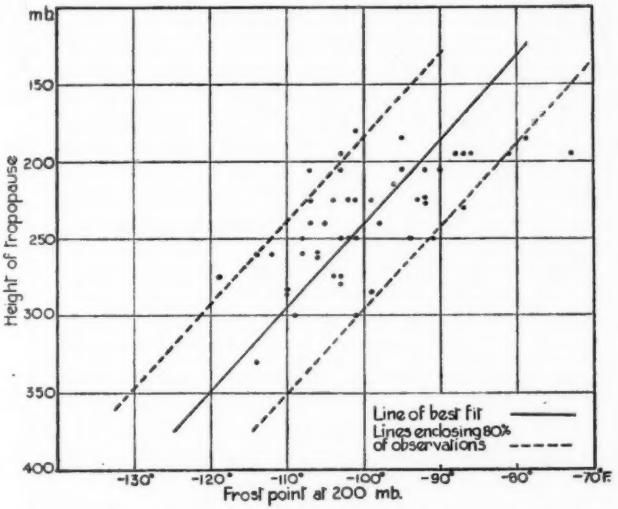

FIG. 5—RELATION BETWEEN TROPOPAUSE HEIGHT AND FROST POINT AT THE 200-MB. LEVEL

A number of other quantities have been correlated with the results set out in Table II below, where (xy) is the correlation coefficient between any variables x and y, P_t, F_t and T_t are the pressure, frost point and temperature at the tropopause respectively. F_{50} the frost point 50 mb. above the tropopause F_{200}, F_{250} and F_{300} the frost points at 200, 250 and 300 mb. respectively and T_{500} the temperature at 500 mb.

TABLE II—SOME CORRELATION COEFFICIENTS

	Correlation coefficient	No. of pairs of values		Correlation coefficient	No. of pairs of values
$(P_t F_t)$	+0·50	64	$(P_t T_t)$	+0·81	64
$(P_t F_{50})$	+0·42	37	$(P_t T_{500})$	−0·61	64
$(P_t F_{200})$	−0·67	48	$(T_{500} F_{200})$	+0·62	48
$(P_t F_{250})$	−0·67	63	$(T_{500} F_{250})$	+0·82	63
$(P_t F_{300})$	−0·62	64	$(T_{500} F_{300})$	+0·79	64

The correlation $(P_t T_t)$ represents a well known fact, the higher the tropopause the colder it is. The correlation between P_t and frost point at the tropopause, F_t, is moderately significant, but that between P_t and the frost point 50 mb. above the tropopause (a level chosen as representative of the stratospheric air) is definitely less so. The three correlations between P_t and the frost points at 200, 250 and 300 mb. are very significant, and these relationships are illustrated as dot diagrams in Figs. 5 and 6 respectively. In each case the full lines are

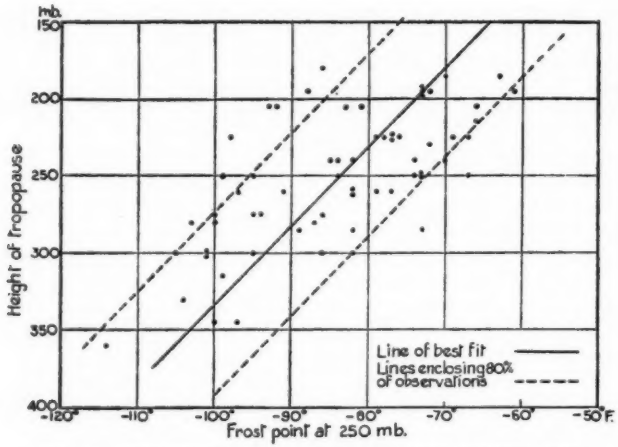

FIG. 6—RELATION BETWEEN TROPOPAUSE HEIGHT AND FROST POINT AT THE 250-MB. LEVEL

lines of best fit whilst the parallel dashed lines enclose 80 per cent. of the observations. They indicate that, given P_c, F_{200} and F_{250} can be predicted to within 10° and 11½°F. respectively on 80 per cent. of occasions. Alternatively, given F_{200} or F_{250}, P_c can be predicted to within 54 or 59 mb. on 80 per cent. of occasions.

The correlations between F_{200}, F_{250} and F_{300}, and P_c are similar in magnitude to those found by Dines (0·7 approx.) and Priestley (0·65)[1] between T_{500} and

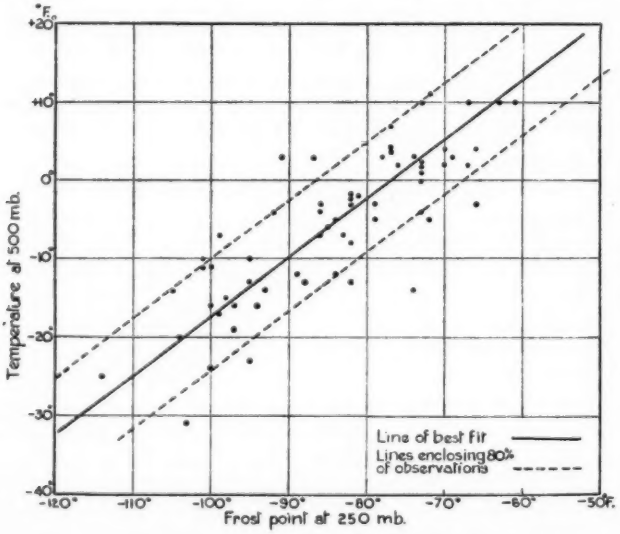

FIG. 7—RELATION BETWEEN TEMPERATURE AT 500 MB. AND FROST POINT AT 250 MB.

H_c, and it seems possible, therefore, that the frost point at a fixed level may be associated with the mean temperature of the troposphere through which the moisture may have ascended. Priestley has shown that T_{500} can be taken as representative of the whole column of air in the troposphere, and that it is in fact preferable to T_m (the mean temperature from 1000 to 300 mb.) for this purpose. Correlation coefficients were therefore computed between T_{500} and F_{200}, F_{250} and F_{300}. The last two are remarkably high, and the highest, that between T_{500} and F_{250}, is illustrated in Fig. 7 as a dot diagram. Here again the line of best fit and lines enclosing 80 per cent. of the observations have been drawn in. It follows that given T_{500}, F_{250} can be predicted to within 9½°F. on 80 per cent. of occasions. It may be significant that the correlation between frost point and T_{500} is least at 200 mb., a level which is predominantly stratospheric. This would suggest that the frost point in the stratosphere is less subject to control by tropospheric processes, or is less of an air-mass characteristic than is the frost point at lower (predominantly tropospheric) levels. Finally a coefficient of −0·61 between P_c and T_{500} was obtained for our observations, and this agrees well with Priestley's value of +0·65 between H_c and T_{500}.

Conclusions.—(1) Frost points in the lower stratosphere (up to 40,000 ft.) over south England are almost invariably low and within the range −80° to −120°F.

(2) There is some evidence, not yet conclusive, for a small seasonal variation in the moisture content of the lower stratosphere, frost points being higher in summer than in winter.

(3) There is often an increase in frost-point lapse rate at the tropopause. A rapid decrease in frost point above the tropopause is most likely to occur when the temperature lapse changes sharply to inversion, and there appears to be an inverse relation between frost-point lapse rate and temperature lapse rate in the lower stratosphere.

(4) Very significant correlations exist between P_c and the moisture content of the atmosphere between 300 and 200 mb., and also between T_{500} and the moisture content of this region. Whilst in the former case there is no very significant variation of the correlation coefficient with height between 300 and 200 mb., in the latter the correlation is definitely least at 200 mb. (a predominantly stratospheric level).

REFERENCES

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A NOTE ON THE 1000–700-mb. THICKNESS AND THE HEIGHT OF THE FREEZING LEVEL OVER THE BRITISH ISLES

By R. MURRAY, M.A.

Introduction.—Synoptic experience shows that there is an intimate relationship between the thickness of the 1000–700-mb. layer and the height of the freezing level. From a sample of observations over the British Isles the cor-

relation has been worked out, with the practical end in view of making use of the 700-mb. prontours (the forecast 700-mb. upper air charts issued by the Central Forecasting Office) as a convenient and systematic method of forecasting the height of the freezing level. The use of this method is limited in practice to air which is commonly classed as " cold " or " polar ", where the 1000–700-mb. thickness is less than 9,500 ft.

Data used.—The 0300 G.M.T. and 1500 G.M.T. British (including Valentia) upper air observations for January, August and April 1–5, 1948, were examined. On the whole, the weather was unsettled during these periods. Although there is some correspondence between the height of the freezing level and the 1000–700-mb. thickness in all cases, it was obvious from the data that the relationship was close enough to be useful in practice only when certain simple synoptic rejection criteria were applied to the ascents. An ascent was rejected from the analysis when (*a*) the 1000–700-mb. thickness was equal to or greater than 9,500 ft., (*b*) an approaching warm front or occlusion was within 400 miles, (*c*) a receding cold front (excluding minor or instability fronts in the cold air) or occlusion was within 200 miles, and (*d*) an anticyclonic centre (minor bubbles of high pressure being ignored) was within 400 miles of the station. No occasions of cold winter continental air were examined. With these provisos the types of air over the British Isles were varied, including very deep and rather shallow cold air. Altogether there were 268 ascents with the thickness of the layer 1000–700 mb. (t_7) less than 9,500 ft. If proviso (*a*) is relaxed, there were 72 ascents with t_7 equal to or greater than 9,500 ft.

Analysis of data.—There were some cases when the freezing-level point was not unique. In one type the surface air was below 32°F., due to nocturnal cooling, with the main freezing level above the ground inversion; in this case the representative freezing level was taken at the upper point and not at the surface. In the second type, which normally occurred with large values of t_7, the cold air was generally rather shallow with the lowest freezing level at some thousand feet and a subsidence inversion above it, causing a more or less thin layer of air to be at temperatures above 32°F.; in this case the representative freezing point was taken at the lowest level.

In order to allow for different mean-sea-level pressures, the 1000–700-mb. thickness (t_7) was correlated with the height of the freezing level above the 1000-mb. surface (H_F) and not with the height of the freezing level above mean sea level. The results are as follows:—

Correlation coefficient = 0·945, with probable error 0·004;

$$H_F = 12{\cdot}33t_7 - 110{,}900 \text{ (regression equation)};$$

standard deviation in H_F for given t_7 equals 460 ft. (to nearest 10 ft.).

From the regression equation we obtain Table I. The regression equation may be put into useful graphical form also.

TABLE I

	feet									
t_7 ..	9,000	9,050	9,100	9,150	9,200	9,250	9,300	9,350	9,400	9,450
H_F ..	100	700	1,300	1,900	2,500	3,200	3,800	4,400	5,000	5,600

Forecasting application.—The thickness of the 1000–700-mb. layer is not broadcast but can easily be obtained from the 700-mb. prontours and the prebaratics (the official forecast of mean-sea-level synoptic charts) which

include the positions of the main fronts and pressure centres as well as isobars, From these forecast charts we readily see whether or not the region of the British Isles (or part of that region) is covered with an air mass satisfying the provisos (*a*), (*b*), (*c*) and (*d*) already stated. Easily remembered approximate values of H_F are 0, 2,500 and 5,000 ft. corresponding respectively to the values 9,000. 9,200 and 9,400 ft. Having obtained H_F it is a matter of a moment's thought to get the height of the freezing level above mean sea level by noting the relevant forecast either of mean-sea-level pressure (prebaratic) or of the 700-mb. contour height (prontour).

That this method is in most cases sufficiently accurate in practice is seen from the fact that the standard deviation in H_F is equal to 460 ft., whilst forecasts normally contain the height of the freezing level only to the nearest 1,000 ft.

The case t_7 equal to or greater than 9,500 ft.—Relaxation of proviso (*a*) decreased the correlation considerably, as the "cold" air in this case was generally very degenerate and shallow with a stable lapse rate of temperature or even an inversion. The correlation method does not give the height of the freezing level with the same degree of accuracy and has not been worked out. However, Table II gives some figures as a guide, although the ranges given for H_F did not include every case.

TABLE II

	feet	
t_7 ..	9,500	9,600
H_F ..	6,000–8,500	8,500–11,000

THE EFFECT OF WATER DROPLETS ON THE BUOYANCY OF A RISING CUMULUS CLOUD

By J. M. CRADDOCK, M.A.

One familiar use of the printed tephigram (Form 2810A) is in the estimation of convective activity. In the usual "parcel" method, we consider a parcel of air which is saturated at the expected temperature at the condensation level, and assume that it rises by virtue of its buoyancy, cooling at the saturated adiabatic lapse rate until its temperature is once more equal to that of the environment. Our estimate of the cloud top is based on this new "equilibrium level", and of intensity of convection on the work done on the parcel during its ascent, as measured by the area on the tephigram between the environment curve and the saturated adiabatic which the parcel is assumed to follow. The sequence of events assumed is a simplified but fair representation of what actually takes place, and probably for this reason, the method has proved a most useful tool in the forecaster's hand. If the physical sequence can be followed more closely on the tephigram, the value of the method may be increased.

The saturated adiabatics on Form 2810A are computed on the assumptions, (*a*) that condensation takes the form of water droplets at temperatures above 32°F. and of ice at temperatures below 32°F., and (*b*) that the products of condensation are removed as they form. It is now accepted that, under convective

conditions, condensation is mainly in the form of water droplets even at temperatures much below 32°F. so that the temperature of a rising cloud parcel will follow closely the saturated adiabatics with regard to liquid water. These " water " adiabatics are shown on the official Form 2810A (overprinted) recently issued by the Meteorological Office, and are reproduced with interpolations as the full lines in Fig. 1. The ice adiabatics which appear on the Form 2810A in general use are shown for comparison by dotted lines. The difference is not negligible.

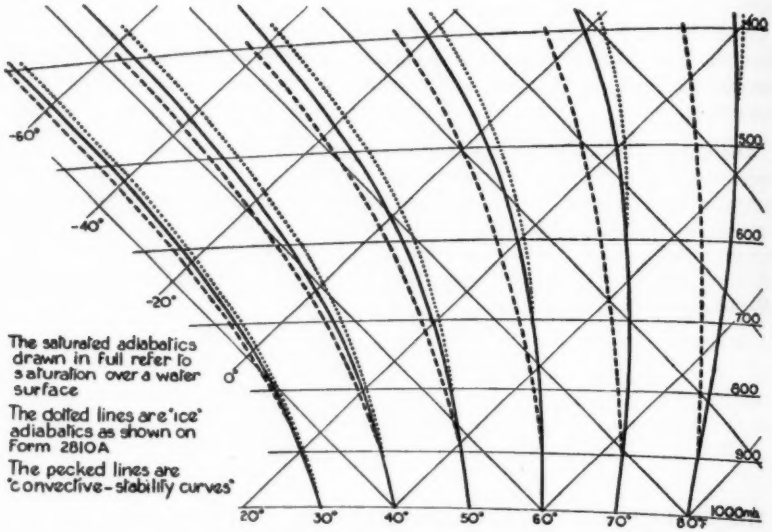

FIG. 1—" CONVECTIVE-STABILITY " CURVES ON A TEPHIGRAM

" Convective-stability curves " give the temperature of an environment having 100 per cent. relative humidity which is of the same effective density at all levels as a rising parcel of air which becomes saturated at 900 mb., and thereafter retains the liquid products of condensation

Furthermore, the growth of a convection cloud is a rapid process during which nearly all the products of condensation are retained within the cloud. For example, a cloud parcel 50 mb. deep which rises at 500 ft./min. for 10 min. will retain over 9 tenths of all droplets of radius 0·002 cm. and a higher proportion of the smaller ones. The heat energy of the retained droplets is thus available, in addition to the latent heat of condensing water vapour, to offset the work done in the expansion of the rising air, and the temperature of the rising cloud mass will fall rather more slowly than it would have done if the products of condensation had been lost. In the terminology used by Brunt[1*], the temperatures of the cloud mass will follow the reversible adiabatic rather than the pseudo-adiabatic. The difference is however small, being inappreciable at low temperatures and hardly exceeding 1°F. under extreme tropical conditions. In what follows the temperature of an ascending cloud parcel is assumed to be given by the " water " adiabatics in Fig. 1.

*See list of references on p. 354.

Although the effect of the water droplets on the temperature of a rising cloud parcel is inconsiderable, the effect on its density is important. A falling raindrop or cloud particle, which has reached its terminal velocity, exerts on the surrounding air a downward force equal to its own weight. This fact has been used, for example, by Buell[2] to compute the down-draught caused by heavy rain, and by H. Ertel[3] to compute the liquid water content of a stationary cumulus cloud. A cloud charged with droplets is heavier (by the weight of the droplets) than a mass of air of the same temperature, pressure and humidity containing no droplets. Thus a droplet-charged cloud, to be in equilibrium, must be somewhat warmer than the environment, so that the residual buoyancy is just enough to support the weight of the suspended water. If the weight of suspended water is Δx gm./Kg., T the absolute temperature of the cloud and ΔT the excess of the temperature of the cloud over that of the environment, then for equilibrium

$$\frac{\Delta x}{1000} = \frac{\Delta T}{T} \qquad .. \quad (1)$$

Now Δx can be estimated at any stage of the cloud development by the excess of the saturation humidity-mixing ratio at the condensation level over its value at the time considered, and equation (1) will give ΔT, the amount whereby the temperature of the environment must be below the appropriate "water" adiabatic if cloud and environment are to be in equilibrium. To illustrate this, "convective-stability curves" are shown in Fig. 1, which assume an initial condensation level of 900 mb., and at all higher levels fall short of the "water" adiabatics by the appropriate value of ΔT.

A rising cloud parcel, which condenses at the 900-mb. level, in a saturated environment represented by the "convective-stability curve" will be in equilibrium throughout its ascent, and will neither absorb nor generate kinetic energy. If the environment is not saturated, its density will be greater than if it was, and the cloud parcel will generate some kinetic energy. It is possible to allow for this by applying the virtual temperature correction to the convective-stability curve (assuming 100 per cent. saturation) and also to the environment curve, and this correction may in fact be necessary if the environment is intensely dry. In European conditions, however, where the environment is usually moist, the virtual temperature correction may be omitted, and the environment curve compared directly with the convective-stability curve. These will intersect near the true equilibrium level and the energy for maintaining the convective circulation is measured by the area between them. The area between the convective-stability curve and the saturated adiabatic represents work done in increasing the potential energy of the suspended water, and so is not available for maintaining convection.

The differences between the convective-stability curves and the saturated adiabatics are material, and it is suggested that the stability of an air mass should be judged by reference to the former. An environment curve lying between the saturated adiabatic and the convective-stability curve will be judged incapable of supporting convection, and in other cases the probable limit of convection will be below that which would have been estimated from the saturated adiabatics.

Experience shows that in temperate latitudes, shower-type precipitation is nearly always associated with the presence of ice crystals in the cloud top, so

that the forecaster who estimates the cloud top (based on the convective-stability curve) to be at temperatures above 32°F. will be disposed to dismiss the risk of showers. If, on the other hand, the rising cloud parcel is expected to penetrate the freezing level, the condensed water which weighs it down may be removed by precipitation. The effective buoyancy of the parcel will then increase and the cloud may rise to the limit estimated from the saturated adiabatic. It should be observed, however, that when the freezing level is penetrated rain formation need not start immediately, and that even when started the process takes time. It may be expected therefore that where the cloud top, estimated from the convective-stability curve, is not far above the freezing level, the rising cloud parcel will come to rest temporarily, until much of the suspended water has been shed.

These theoretical arguments were prompted by observation in the tropics, and serve to explain some characteristic features of tropical convection[4,5]. At lower temperatures the effect of the weight of the retained water droplets on the buoyancy of a cloud is less, but still seems sufficient to require attention by the routine forecaster on the lines suggested.

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LUMINOUS NIGHT CLOUDS

By J. PATON, M.A., B.Sc.

A strikingly brilliant display of luminous night clouds was visible in Scotland during the night of July 10–11, 1949 after a weak though unmistakable occurrence on the previous night. The clouds appeared along the northern horizon in an otherwise empty sky about half an hour after sunset and soon stood out sharply defined against the darkening background. In shape and form they were identical with mixed cirrus filosus and cirrostratus and could be distinguished from these normal clouds only by their luminosity. Their brilliant blue-white colour matched the twilight glow. Long parallel uniformly spaced cirrus-like streaks stood clearly defined in places against a dark background; sometimes curving to assume the shape of roughly coiled rope. In other parts the streaks were backed by a sheet resembling cirrostratus. The streaks showed only a slow change in form with time, each remaining easily identifiable on photographs taken after an interval of some twenty minutes or so. By contrast, the background showed continuous change, sometimes appearing as a perfectly uniform sheet, then suddenly developing within itself thin parallel waves, roughly perpendicular to the much brighter and more solid streaks (see photographs facing p. 356). This appeared to correspond precisely to the change from cirrostratus nebulosus to cirrocumulus undulatus. As midnight approached both the altitude and extent of the luminosity slightly diminished, then slowly increased again during the early hours of the morning. When first observed the clouds extended from 24° west to 56° east of north, the maximum

altitude being 11·5°. By midnight the altitude had fallen to nearly 10° and the western limit was now 18° west of north. The area of luminosity was thus at a minimum with the sun at its lowest point below the horizon. Thereafter, both the luminous area and brightness increased, the former progressing eastwards with the sun, and eventually fading in the brightening sky before dawn.

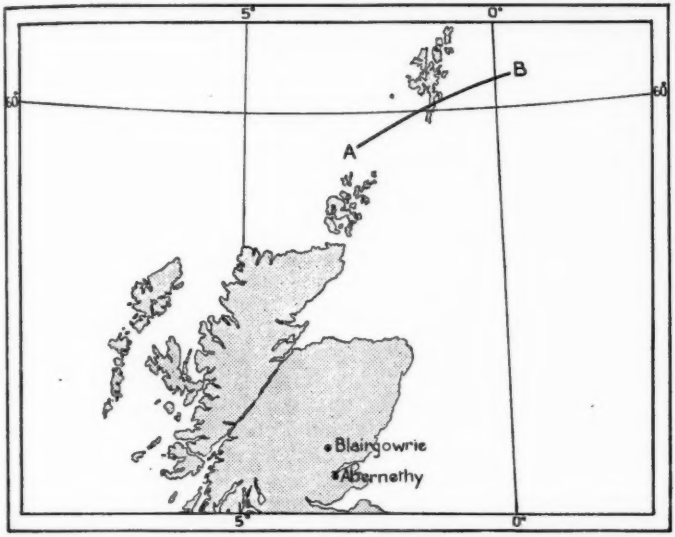


FIG. 1—MAP SHOWING THE ESTIMATED POSITIONS OF THE LUMINOUS NIGHT CLOUD ON THE NIGHT OF JULY 10–11, 1949

Pairs of simultaneous photographs by Stœrmer-Krogness auroral cameras were obtained at Abernethy and Blairgowrie, 27·6 Km. apart. Using Stœrmer's methods for measuring parallactic photographs of aurora, this series will yield measurements of the height and position, the speed and direction of movement and the distance between successive crests of the clouds. Measurements of the two corresponding photographs used here as illustrations show that the upper "streak" marked AB on the photograph taken at Abernethy, extended roughly in a north-east to south-west direction over southern Shetland at a height of approximately 89 Km.

Mr. Schröder of Holmestrand secured excellent photographs of this display on daylight Kodachrome. Professor Stœrmer hopes to use them with a simultaneous position of the clouds, interpolated from our photographs to make measurements using the base line Holmestrand-Abernethy.

During the night of August 1–2, the Norwegian network secured 42 sets of simultaneous photographs from three stations, Oslo, Holmestrand and Askim, of a further display in the north and north-east. This was not visible in Scotland.

Although earlier observations of these rare clouds are probable, so striking is their appearance, the first recorded observations were made in 1885. From then until 1894 they occurred very frequently indeed and in most brilliant forms. Although so tenuous that stars shine through them without apparent reduction

in brilliance, on some occasions at this time luminosity was sufficiently great to cause shadows of terrestrial objects to be cast on the ground. Sometimes the clouds extended over the zenith to the south-east horizon. Omond observed them from Ben Nevis Observatory during the summers of 1887 and 1888 " on almost every clear night ". The information collected during this period was analysed by Jesse[1]*, who himself succeeded in measuring their height by photographic methods. He found that they were situated at heights of about 82 Km. and were observed only between late May and mid August and only in latitudes between 45° and 62°. They travel almost invariably with a westerly component, from north-east before and from east-north-east after midnight, with speeds often greater than 100 m./sec. On one occasion, Jesse recorded a speed of 300 m./sec. The distance between successive wave crests was found to be 9 Km. Their spectrum showed no emission lines but the Fraunhöfer lines were easily seen. Jesse then concluded that they consisted of " foreign matter, perhaps the products of condensation of gases projected to great heights during volcanic eruptions ", their luminosity being due to their reflection of light from the sun, 10°-18° below the horizon.

Størmer[2,3,4,5] employing his network of photographic auroral stations has confirmed Jesse's measurements of height, velocity and distance between wave crests and has suggested examination of their nature and height by radio and radar methods.

Vestine[6] has made a statistical examination of observations between 1885 and 1923 and has shown that the distribution of nights of occurrence closely follows a normal error curve, the most likely time of occurrence being ten days after the summer solstice. It is then, too, that the clouds are most brilliant. He compares the yearly frequency of appearance of the clouds with yearly occurrences of volcanic eruptions, meteor showers and great comets and is led to the conclusion, to which Professor Størmer subscribes, that the evidence favours a cosmic rather than a volcanic origin for the constituents of the clouds. The remarkably frequent and brilliant displays of the period 1885-94, which had been usually ascribed to residual dust from the Krakatoa eruption of 1883, are deemed more likely to be associated with the equally remarkable number of meteor appearances, showers and great comets of the period 1880–87. That the great eruption of Katmai, Alaska, in 1912, was succeeded by no marked increase in frequency of these clouds, while the great Siberian meteor of 1908 was followed immediately by most brilliant displays is cited in support of this view. On the other hand, Vegard[7] and others[8,9] have suggested that the clouds may be composed of ice crystals.

Whatever uncertainty there may be concerning the nature and origin of the cloud particles, there can be no doubt that they are minute in size. The nature of their spectrum, revealing that their light is scattered sunlight, and their predominantly blue colour show that their diameter must be of the order of the wave-length of visible light. In the display of July 11, the lower edge of the clouds was tinged a reddish-brown colour soon changing to blue with increasing elevation, the maximum luminosity being at the maximum elevation. Observed through blue glass this increase in blue luminosity with elevation was even more clearly seen. On the other hand, when observed through red glass,

*These numbers refer to the list of references on p. 357.

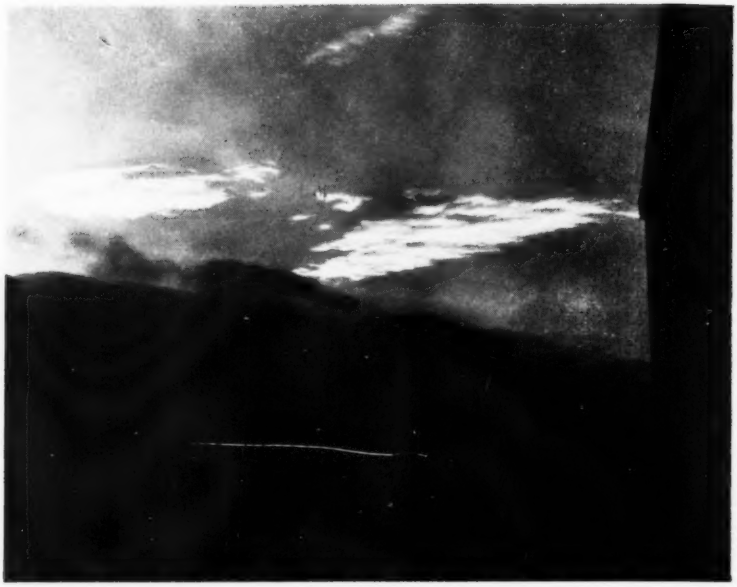
Photos reproduced by the courtesy of J. F. McKellican

LUMINOUS NIGHT CLOUDS SEEN FROM BLAIRGOWRIE

Photos reproduced by the courtesy of J. Paton

LUMINOUS NIGHT CLOUDS SEEN FROM ABERNETHY

Parallactic photographs of luminous night clouds at 0019 G.M.T., July 11, 1949, from Abernethy and Blairgowrie 27·6 Km. apart. The star at the centre of the Blairgowrie picture and to the right of the centre of the Abernethy picture is Capella



IRIDESCENT CLOUD AT ALDERGROVE, 1545, NOVEMBER 24, 1948

(see p. 366)

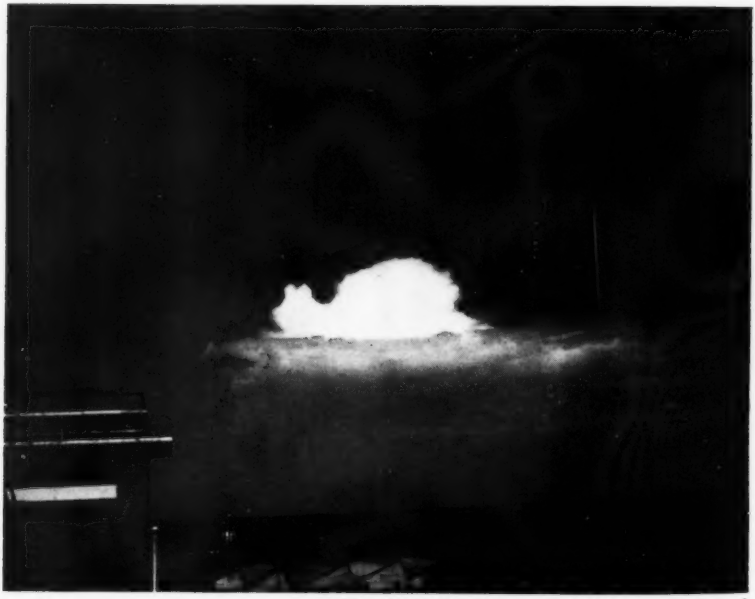


Photo by the Royal Aircraft Establishment, Farnborough

ALTOCUMULUS CASTELLATUS AT FARNBOROUGH, 0840, JULY 13, 1945

The height of the base of the cloud is 8,000–10,000 ft.

Photo by R.A.F.

CUMULONIMBUS IN THE ENGLISH CHANNEL, 1909, AUGUST 27, 1945
Taken from 20,000 ft. near the Channel Islands looking south-south-eastwards. A thundery trough is approaching from the south

Photo by R.A.F.

CUMULUS AND CUMULONIMBUS OVER BRITTANY, 1235, JULY 2, 1945
Taken from 18,000 ft. looking north-north-east, showing cumulus development after the passage of a cold front

Photo by R.A.F.

RAPID CUMULUS DEVELOPMENT AT DISHFORTH
(see p. 368)

the clouds were just recognisable and red luminosity appeared to be uniform from the base to maximum elevation. The reddish-brown colour and diminishing luminosity towards the base of the clouds may be due to increasing selective atmospheric scattering in the increasing (with decreasing elevation) effective thickness of air during the passage from the cloud to observer. It may also result from depletion, mainly in the lower parts, of the illuminating solar beam during the passage of the light through the atmosphere before it reaches the clouds. Indeed, Stœrmer has shown that the luminosity decreases rapidly when the solar rays incident on the cloud traverse the atmosphere at heights lower than about 30 Km. from the earth's surface.

The main interest of these clouds to the meteorologist lies in the fact that, with meteor trains and perhaps certain residual forms of aurora, they provide the only direct means of ascertaining air movement at these high altitudes. Since they are situated near the earth's shadow, the information concerning air movement in this region may be especially interesting. But the most extraordinary feature of these luminous night clouds is their persistent appearance at the same height, between 80 and 90 Km.

Whether they are comprised of dust or ice, this constancy of height implies the existence of a minimum of temperature at the cloud level, for only then can, (*a*) the drift of dust to and its concentration in a layer at uniform height, or (*b*) the formation and persistence of a stratum of ice crystals, be explained. The latter requires that the temperature be of the order of 160°A. Evidence in support of the existence of such a temperature minimum comes from Whipple's[10] examination of meteor-track photographs, which yields an estimate (apparently in good agreement with V-2 rocket results up to 70 Km.) of the gradient of density and so of temperature. This reveals a temperature maximum of the value 350°A. at 60 Km. and a minimum of 200°A. at 80 Km., a temperature-height distribution that accords with the occurrence of these clouds at 80–90 Km.

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OBSERVATIONS OF A THUNDERSTORM FROM SMALL CUMULONIMBUS

By F. H. LUDLAM

On October 4, 1948, a thunderstorm was reported from Bassingbourn and Duxford from unusually small thunderclouds whose tops were observed by several aircraft. Details in the following account of the storm have been supplied by the Meteorological Officers at the two stations.

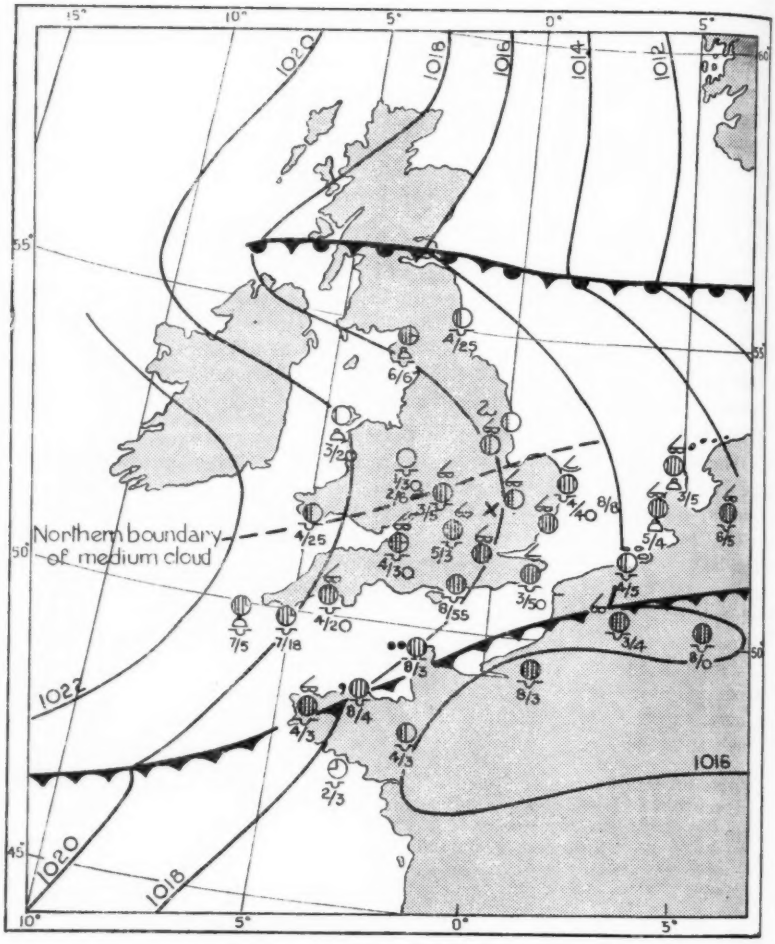

FIG. 1—SYNOPTIC CHART, OCTOBER 4, 1948, 0600
The position of Bassingbourn is marked by an **X**

In the early morning the British Isles were covered by a northerly air stream behind a cold front which at 0600 lay along the coast of north France (Fig. 1). A layer of medium cloud on the cold-front surface extended northward over the English Channel and the south of England, with its northern boundary lying roughly along a line from Pembroke to The Wash. The medium cloud was broken in many places and contained some castellatus; below it there was at first little or no low cloud, but by 0800 some cumulus and stratocumulus was reported. The edge of the system of medium cloud was moving south as the cold front receded, and by 0900 the upper cloud lay almost entirely south of a line from Hartland Point to Yarmouth. At this time Bovingdon reported a shower,

and Wittering a shower in the last hour. Both stations reported large amounts of low cloud, but Bassingbourn experienced a slight shower at 0820 from upper cloud and first observed large cumulus at 0850. Examination of the Downham Market 0800 radio-sonde sounding (Fig. 2) suggests that the cumulus which was forming about this time, probably helped locally by orographic ascent, might continue to grow to between 15,000 and 16,000 ft., where the temperature was about −18°C. Between 0900 and 1000 a group of showers approached the Duxford-Bassingbourn area, and at 1015 both stations reported a thunderstorm with moderate to heavy rain. Two brilliant lightning flashes were observed from Bassingbourn and at Duxford about six separate peals of thunder were heard. Meteor pilots who were in the area at the same time reported chaotic cloud up to medium levels with cumulus and cumulonimbus tops reaching up to between 12,000 and 15,000 ft. (one pilot saw a lightning flash near Bassingbourn). A Spitfire of the Aero Flight, R.A.E., was also in the neighbourhood, and Mr. Jones of the East Hill radar station (near Dunstable), who was controlling its investigation, has kindly made available records which make it quite clear that the aircraft flew through the same cloud mass. The pilot did not report any thundery activity, but confirmed that the cloud tops were at about 13,000 ft. The precipitation echoes observed by Mr. Jones reached a maximum height of about 12,000 ft.

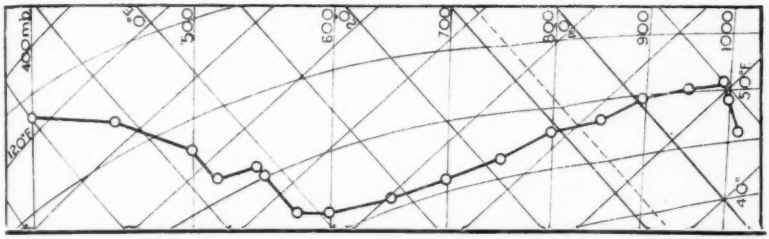

FIG. 2—RADIO-SONDE SOUNDING, DOWNHAM MARKET, OCTOBER 4, 1948, 0800

The deterioration did not last long; about 1030 the rain ceased at both Duxford and Bassingbourn, and Bassingbourn reported that at 1100 the storm cloud could be seen to the south-east, but that otherwise there were only small cumulus in the sky, with no trace of the medium cloud which had been extensive before the storm. The Meteorological Officer at Duxford remarked that the improvement was typical of that usually experienced after the passage of a moderately vigorous cold front. This must be regarded as fortuitous, however; an examination of the synoptic data does not reveal any secondary cold front, but does show that the system of medium cloud was still moving away southward and that the thunder shower had occurred near its northern limit. It is remarkable that farther south showers were later reported (from Croydon and Scilly) near the edge of the medium cloud system, but that farther north the cumulus over inland areas south of 53°N. became small as the air became drier and the cloud base rose. It seems possible that the medium cloud was producing a considerable ice-particle precipitation which mostly evaporated long before reaching the ground, but which served to effect a kind of natural "seeding" of the tops of some of the larger cumulus.

Nevertheless it is clearly evident that a slight thunderstorm was produced by cumulonimbus whose tops were below 15,000 ft. (temperature above − 20°C.), and it is believed that thunder from such a small cloud is very unusual. Elsewhere the writer has suggested that a temperature of about − 32°C. in the cloud tops may be a threshold temperature separating thunderclouds from showerclouds. Further evidence for or against this view would be very welcome.

BASIS FOR EXTENDED FORECASTING AS PRACTISED IN THE UNITED STATES WEATHER BUREAU

By J. NAMIAS

A large and appreciative audience, both from within and outside the Meteorological Office, attended a lecture given at the Science Museum on September 26 by Mr. J. Namias, on the subject quoted in the title. This was the second of the special lectures by distinguished meteorologists visiting this country which we have had the privilege of hearing this autumn, the first by Dr. T. Bergeron having been reported in the November 1949 issue of the *Meteorological Magazine*.

The Director, introducing Mr. Namias, said that the audience would have been even larger were it not for the prior claims on forecasters' time of the R.A.F. exercise " Bulldog ". The name of Mr. Namias was well known to all, first, as a leading exponent of the technique of isentropic analysis, and latterly as the Chief of the U.S.W.B. Extended Forecast Section. The fact that the extended forecasting experiment in this country had been the subject of one of our own discussions early this year would make Mr. Namias' lecture all the more interesting.

Mr. Namias, in a brief historical introduction, explained that research by the Weather Bureau and the Massachusetts Institute of Technology into the problem of extended forecasting was started by a resolution of Congress following the severe droughts in the United States in the early 1930's. After some five years of preliminary investigations the regular issue of forecasts covering five days was begun in 1940, the basic research meanwhile proceeding side by side with the operational work. There are two essential features of the United States technique of extended-range forecasting; the first, which will be generally agreed, is the necessity of considering the atmospheric circulation over at least the whole hemisphere; the second, which might not find such general acceptance, is the necessity for viewing broadly the time sequence of events, by working principally with mean charts for the five-day period. The mean-map technique smooths out the transitory features and gives true prominence to the semi-permanent centres of action, the significance of which all must recognise.

With the aid of a series of clear and purposeful slides, Mr. Namias then gave an account of the U.S.W.B. extended forecasting practice. The basic tool is the forecast five-day mean 700-mb. contour chart, which generally shows a circulation round the pole, on which are superimposed large-scale slow-moving ridges and troughs, more or less regularly spaced round the hemisphere (Rossby long waves). These troughs are the aggregates of the faster-moving daily troughs, and mark the positions at which the daily troughs reach their greatest development. Topographical features serve to " anchor " troughs or ridges in certain longitudes, and resonance induces a series of troughs and ridges downstream,

whose movement and spacing can be estimated from Rossby's well known formula. Strictly, the formula applies to actual troughs and ridges, but has been modified empirically to apply to mean charts. The forecast mean surface chart is constructed from the mean 700-mb. chart by adding the field of normal thickness, modified to allow for expected thickness anomalies.

These physical considerations are supplemented by kinematical methods based on extrapolations and trends, and the forecast mean charts are constructed so as best to take account of all these factors. The interpretation of the chart in terms of forecast weather is in part an objective process; the basic forecast gives expected five-day anomalies of temperature and precipitation which are arrived at from supplementary statistical material showing the distribution over the United States of the correlation between these anomalies and the anomalies of the 700-mb. pattern derived from the forecast chart. Experience has shown that this is a reliable method of forecasting general conditions over a period. Although daily forecast charts for the five-day period are prepared also, only small success has so far been achieved in forecasting in detail the weather for any place beyond two or three days; the U.S.W.B. has gone no farther than our own service in meeting, for example, the demand for advance forecasts for public holidays.

A considerable number of questions, mainly on points of detail in forecasting procedure, were put by members of the audience and answered by Mr. Namias. The Director then expressed the thanks of all present for a most enjoyable lecture, outstanding for its clarity and ease of presentation of a subject, which surely must have been most difficult to treat so adequately and yet to compress into the time available.

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METEOROLOGICAL OFFICE DISCUSSION

The first discussion of the 1949–50 series, held at the Imperial College on October 3, 1949, dealt with the results of the United States Thunderstorm Project, and was opened by Mr. F. E. Coles.

The U.S. Thunderstorm Project was organised by the National Advisory Committee of Aeronautics U.S. Weather Bureau, U.S. Navy and U.S. Air Force to investigate the structure of thunderstorms with the aim of evolving safer flying techniques. The Project was directed by Dr. H. R. Byers. It was carried out in two phases, the first to study the subtropical thunderstorms of Florida, and the second the frontal and air-mass thunderstorms in the higher latitude of Ohio.

The thunderstorms were observed by a dense network of ground stations, one to two miles apart with automatic recording instruments, and by radio-sonde and radar wind stations. Specially equipped P61 aircraft made simultaneous traverses through thunderstorms at altitudes between 5,000 and 26,000 ft., normally with 5,000-ft. height separation, and observed turbulence intensity, extent of cloud and hydrometeors. Ground radar stations guided the aircraft and studied the development and movement of the thunderclouds. Frequent photographs were taken of radar scopes and aircraft instruments and all observations were carefully synchronised.

Results indicated that thunderstorms usually consisted of several turbulent convective cells about 1–5 miles in diameter and in various stages of development, separated by relatively smooth corridors about a mile or less wide. Single-cell storms were rare, although each storm probably originated as such, but other cells soon formed once the first cell had produced rainy conditions. Radar and rainfall patterns confirmed a cellular structure.

There appeared to be three stages of development in each cell:—

In stage 1 there is convergence at all levels, and an up current prevails throughout the cell, possibly attaining a speed of 100 ft./sec. in well developed cells, consequently condensation and growth of water-drops occur.

In stage 2, which is the peak stage, water-drops fall to the surface and drag a certain amount of air with them, so causing a down draught to develop, while cooler, drier air is also frictionally entrained from the environment by the down draught, which is further cooled by evaporation of rain, and sinks towards the surface. Many striking features of the thunderstorm, such as the heavy rain, first gust squall line, fall of temperature and rise of pressure are apparently associated with the cold down draught air. On reaching the surface the cold air spreads out and soon outruns the rain area and sometimes appears up to 12 miles ahead of the original radar echo. This process often appears to trigger the formation of a new radar echo which forms behind the first gust line and may often merge into the parent thunderstorm. New thunderstorm cells usually form 3 miles or less down wind from an existing cell or between two cells less than 3 miles apart. In this stage, observations showed convergence at most levels of the cell, but divergence above about 25,000 ft. and below 5,000 ft. The surface divergence maximum was related to the maximum intensity of surface rainfall. The down draught does not extend much above 25,000 ft., probably because at higher levels there is insufficient water to produce significant precipitation.

In stage 3, termed the anvil or dissipating stage, the down draught spreads across the lower part of the cell until the up draught becomes of secondary importance. Eventually down draughts decreasing to about 20 ft./sec. or less occur throughout the lower levels of the cell, while above 25,000 ft. there are only small vertical motions. Rain becomes lighter and the thundercloud starts to dissipate first at the lower levels.

Upper wind and aircraft data confirmed the fact of entrainment of the environment by up and down draughts. Consequently the lapse rate in the up draught normally exceeded the saturated adiabatic, while the down draught was cooler than if it had gained heat at the saturated adiabatic rate.

The main flight hazards to aircraft in thunderstorms were turbulence, hail, lightning and icing. Pilots found that turbulence was least at 5,000–6,000 ft., and generally greatest between 15,000 and 20,000 ft., but there was little difference between the frequency of heavy turbulence at medium and high levels. It was important to distinguish between draughts and gusts. Draughts were the large scale up and down currents usually continuous over several thousand feet and lasting up to 30 min. with varying speeds. Gusts were smaller scale more transient phenomena similar to surface gusts. Normally draught velocities greatly exceeded gust velocities, but the larger gusts were invariably associated with strong draughts. Radar measurements suggest that up-draught velocities increased with height up to about 10,000 ft. below cloud top.

Hail was encountered by project aircraft mainly near the freezing level and least at the lowest and highest levels flown, and caused no major damage.

Lightning strikes on the aircraft occurred mainly at 16,000 and 26,000 ft. at temperatures from + 2°C. to −25°C. but no major radio failure or serious damage occurred.

Wet snow packed on the leading edges of the aircraft on about a quarter of the traverses, and reached a thickness of about a quarter of an inch, but icing was never a serious hazard in the relatively short period aircraft were flying in thunderclouds.

Commenting on the investigation Mr. Coles said that although over 1,300 traverses of thunderstorms were made no details were given of the number of separate storms investigated. Further investigations below 5,000 ft. and above 26,000 ft. were desirable. This was particularly necessary above 26,000 ft. as it appeared that up draughts and associated turbulence might increase with altitude above 26,000 ft. Judging from the maximum altitudes of thunderstorm echoes measured by radar and the fact that actual cloud tops normally exceed these figures, it seemed likely that on some occasions the thunderclouds penetrated into the stratosphere.

The Director, opening the discussion, asked how convergence and the speed of draughts were calculated, whether the formation of secondary echoes behind the first gust line was due to mechanical lifting by the cold air and whether there was any strong evidence of tops of thunderclouds penetrating into the stratosphere.

Mr. R. G. Veryard referred to desert duststorms and thunderstorms, and thought that evaporation of rain into dry air was one of the main factors in the cold down draught. He asked whether the Americans had related wet-bulb temperatures to the level from which the air had come, and how various intensities of precipitation had been observed from aircraft.

Mr. J. L. Galloway emphasised that the investigation gave no information about conditions above 26,000 ft. The work had been done in strong P.61 aircraft but would similar results apply to the average heavy bomber ?

W/Cdr. S. W Hughes, Assistant Director of Training (All Weather), said that he had himself flown in a number of traverses made by aircraft of the Project and had later been closely concerned with the discussion of the observations. The P61 aircraft used were not specially strengthened, and the results can be applied to any aircraft and safe penetration speeds calculated. Some heavy aircraft did not appear suitable for thunderstorm flights in which a 43-ft./sec. maximum gust might be encountered. However, the All Weather Airline from Washington to Clinton had been flying in C54 aircraft through many thunderstorms in the past 2 years, but flew below 10,000 ft. during thunderstorms to avoid the worst turbulence.

Mr. R. F. Jones thought that the risk of icing had been underrated, as there had been two occasions when the R.A.E. Spitfire working with East Hill radar station (Bedfordshire) had been forced to abandon a thunderstorm traverse owing to severe icing, and one occasion when the V.H.F. aerial had been broken due to icing. Nor was he convinced that the regions between thunderstorm cells were quite as calm as suggested. Although the edges of the radar echo

columns appear to be the most turbulent, some quite large gusts had been recorded in the troughs between the columns. The definition of a thunderstorm based on radar-echo tops exceeding 25,000 ft. was rather arbitrary, and it seemed probable that this height was rather low and that a large proportion of the clouds flown through were not actually thunderstorms. The strongest gust experienced by the R.A.E. Spitfire was at 30,000 ft., and it appeared that turbulence increased upwards in a thundercloud, until a height of rather less than half the vertical extent of the cloud was reached, and then remained more or less constant until near the top of the cloud.

As regards down draughts, comparison of R.A.E. Spitfire flights with radar echoes suggests that the typical echo columns are associated with up draughts, and that down draughts are associated with a part of the cloud clear of echo. It may be that the greatest echo is associated with large raindrops which cannot fall to the ground because the up draught is too strong, but if heavy rain is associated with the down draught this should also give an echo. Possibly this discrepancy arises from the assumption that water accumulates in the up draught until it could no longer be supported, but this overlooked the limiting size to which a raindrop could grow. Further growth beyond about a quarter of an inch diameter would result in disruption, and the smaller drops so formed would be carried more quickly upwards. If the upward current now spreads out near the cloud top, the vertical component of the current decreases and the small drops would then fall down outside the vicinity of the strongest current and probably in a down draught. Such small drops would not give a radar echo, nor the heavy thunderstorm rain, which Mr. Jones felt was associated with the up draught, but strong echoes would be obtained from the large drops travelling upwards in the up draught or possibly slowly down in the weaker parts of the current. He wished to know if there were any alternative ideas as to the cause of the down draught.

Mr. C. K. M. Douglas said that the observed frequency of hail was less than might be expected. In the high Alps heavy hail or soft hail was usually, if not always, present at the phase of maximum activity when a large cumulus head first became glaciated. Melting of hail would reduce the wet-bulb potential temperature of a descending air mass, but this would not be done by mixing if the wet-bulb potential temperature decreased upwards as it should do in a thunderstorm area. For students of clouds the position would be clarified if the presence of a number of cells within a unit cumulonimbus cloud were distinguished from cells which correspond with such clouds. A diameter of 1–5 miles had been mentioned, but 1 mile was small in relation to that of a normal well developed large cumulus. Large cumulus in lines or groups often reached an advanced stage of development before any one of them produced a shower.

Mr. J. S. Sawyer said that the use of radar in the Project directed attention to the life history of the radar echo rather than that of a true circulation cell. If the up currents were inclined, the large water-drops which caused the echo might fall out into a fresh mass of air which would be cooled and descend. The change from upward to downward motion in the radar echo did not necessarily imply a reversal of the circulation. Mr. Sawyer also said that it was difficult to believe that entrainment of air could have a major effect on the lapse rates, because it would require the intimate mixing of two masses of air a mile or more in diameter in a period of about ten minutes—was turbulence great enough for this?

Mr. J. M. Craddock said that large convective clouds generally consisted of a group of towers rising close together and might be expected to show a cellular structure. He thought the weight of the suspended water which produced the down draught was also important during the early stages of convection and referred to work published on p. 351 of this issue of the *Meteorological Magazine*. Convection of the intensity described was a very effective means of transferring energy upwards, while the supplies of energy obtainable from air-mass instability or from current insolation were comparatively small. Hence the mean fraction of any large area occupied at any instant by active convective cloud must be very small.

W/Cdr. Hughes said it was not true to say that aircraft should always be slowed down, as in some cases the best penetration speed was above the cruising speed. He did not think there were many people who had qualms about down draughts at low levels, but considered that hail was one of the greatest hazards. He hoped that the R.A.F. might investigate thunderstorms in the Far East, possibly in collaboration with the United States Air Force.

Mr. A. W. Brewer pointed out that many of these ideas were quite old. Many years ago, Normand showed that a down draught is necessary for the release of the full amount of energy of a thunderstorm while the entrainment of air by jets was well known to aerodynamicists, and was considered in detail in the wartime FIDO work.

Mr. Coles stated in reply that most of the convergence figures were calculated by a graphical method due to Bellamy. Draught velocities were normally estimated from aircraft height changes in a given interval on occasions when no appreciable movement of aircraft controls occurred. The cause of secondary radar echoes behind the first gust line might well be a trigger action started by lifting at the miniature cold front. There seemed to be a strong probability that on some occasions thundercloud tops penetrated the stratosphere. In reply to Mr. Veryard the levels from which down draughts originated had not in the papers considered been related to wet-bulb temperatures. In reply to Mr. Sawyer it was probable that large horizontal gradients of temperature existed in the draughts and complete mixing only occurred near the edges.

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   (*a*) Report No. 1—Operation and activity of the thunderstorm project to September 20, 1946. Washington, D.C. 1946.
   (*b*) Report No. 2—Summary of Pilot reports. The thunderstorm project, phase I. Washington, D.C. 1947.
   (*c*) Report No. 3—Operation and activity of the thunderstorm project, April 1 to October 1, 1947. Washington, D.C. 1948.
   (*d*) Joint meeting of airlines meteorologists and thunderstorm project personnel, Chicago, June 1, 1948. Washington, D.C. 1948.
2. Washington, D.C., U.S. Weather Bureau. Report on thunderstorm conditions affecting flight operations. *Tech. Pap. weath. Bur., Washington, D.C.*, No. 7, 1948.
3. BYERS, H. R.; Thunderstorm structure and circulation. *J. Met., Lancaster, Pa.*, **5**, 1948, p. 71.
4. BYERS, H. R. and HULL, E. C.; Inflow patterns of thunderstorms. *Bull. Amer. met. Soc., Lancaster, Pa.*, **30**, 1949, p. 90.

ERRATUM

Page 318, Fig. 2 caption, line 4; *for* "The continuous lines are isonormals" *read* "The continuous lines are isanomalies."

METEOROLOGICAL RESEARCH COMMITTEE

The 58th meeting of the committee was held on October 12. The committee was primarily concerned with the general direction of the research effort of the Meteorological Office but there was some detailed discussion of difficulties encountered in the investigation of the high atmosphere by the use of a high-power pulsed light searchlight.

The 6th meeting of the Instruments Sub-Committee of the Meteorological Research Committee took place on October 27. The use of " window " in conjunction with radar for the measurement of winds at high altitudes was discussed and it was agreed that the method is practicable.

There was also some discussion of the means of avoiding radiation errors in radio-sondes. There is some evidence that such errors can be reduced to insignificant values by the use of temperature elements in the form of very fine wires. This matter is being pursued.

Two other matters connected with radio-sonde instruments—methods of comparison of height measurements by radio-sonde and radar* and the errors of radar wind observations on weather ships—were also considered.

LETTERS TO THE EDITOR

Multiple tropopauses

In Dr. Scrase's interesting article in the October issue of the *Meteorological Magazine* reference is made to " a multiple tropopause of the type first suggested by Bjerknes and Palmén " in 1937. I had almost forgotten that I myself pointed out much earlier, *viz.* in 1922, tha tthis phenomenon sometimes occurred in our latitudes. Using the data of the ballons-sondes of Paris and Uccle of October 5, 1911, and the pilot-balloon ascents of Copenhagen and Uccle, I showed that over Belgium on that date the polar tropopause was at about 8·6 Km., the change from polar stratosphere to tropical troposphere at about 11 Km. and the tropical tropopause at about 15 Km. A note on the subject was published in the *Quarterly Journal of the Royal Meteorological Society, London*, **49**, 1923, p. 16.

Also Ramanathan pointed out in 1929 that multiple tropopauses occur over northern India between the months of November and April. The major references to his work are *Mon. Weath. Rev., Washington, D.C.*, **57**, 1929, p. 64, *India met. Mem., Poona*, **25**, 1930, p. 163, and *Nature, London*, **132**, 1933, p. 932. Over Agra the lower transition occurs at 12–13 gdKm. and the second at about 17 gdKm. In the *Nature* article he showed also, with references to published upper air data, that multiple tropopauses occur over the United States in summer.

A. H. R. GOLDIE

October 14, 1949

Remarkable cloud spectacle seen at Aldergrove

On the afternoon of November 24, 1948, a most beautiful cloud spectacle was observed at Aldergrove. There were two rather small patches of altocumulus, lenticular in form and in a slowly dispersing condition, situated 20–25° above the horizon to the south-west of the station. This cloud, while it was definitely altocumulus, was doubtless rather high for medium cloud, being estimated at about 20,000 ft. The observer has no doubt, however, that

* HARRISON, D. N.; *Met. Res. Pap., London*. No. 504, 1949.

it was not at any phenomenal height, for there was ordinary cirrus about at the time, this latter being definitely above the level of the cloud in question. Along the south-western quadrant of the horizon was a bank of strato-cumulus, base near 2,000 ft., top 3,000–4,000 ft., the edge of which formed a line 5–10° above the horizon. Behind this layer, in the south-western sky, by 1530 G.M.T., the sun, red with the rather thick haze, had set, but of course was still shining on the medium-cloud patches. At this time there appeared in these lenticular patches a remarkable iridescence, the colours ranging from a deep violet running in a band around the whole edge of each cloud, followed by similarly shaped bands of green, yellow (rather fainter) then red. The successive boundaries of each colour clearly followed the exact pattern of the outline shape of the cloud. Within the last fringe, the red, was a patch of brilliant green, occupying the interior portions of the cloud. It was remarkable to see that, while there was some tendency for the successive colours from the violet inwards to the red to merge a little from one to the next, there appeared no such boundary conditions between the red and the interior green patches, the change between these being quite abrupt. It has just been remarked that there was some sign of gradual transition from one colour to another from the outer edge of the cloud into the red fringe, but the transition was really far more abrupt than it is between the successive colours of the ordinary rainbow; moreover while close examination showed that all the spectrum colours were present, it was only the violet, green and red which appeared clearly distinctive, and very brilliant.

H. W. HILL.

A photograph of the cloud referred to above was taken at R.A.F.N.I. Headquarters at 1545, about 15 minutes after the iridescent cloud was first observed at the Aldergrove Office a mile away (see centre of this Magazine).

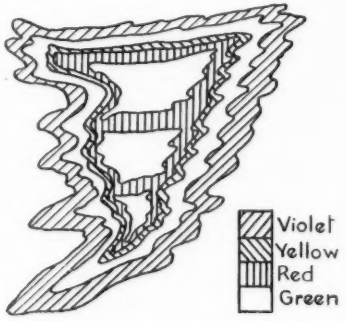


FIG. 1

At this time the predominating colours were green and pinkish red and both were vivid. These two colours were positioned in such a way that the protuberances in the cloud were pinkish red and the hollows vivid green and gave a remarkable patchlike colour effect of great beauty.

The three main patches of green drawn in the sketch supplied by Mr. Hill (Fig. 1), compare very well with the three main dark patches or hollows in one of the two iridescent clouds shown in the accompanying photograph taken some

fifteen minutes later. Fading of the colours became fairly rapid and only a faint indistinct green interspersed with patches of reddish brown remained after ten minutes (from 1545).

An interesting feature brought out by the photograph is the faint nebulous background of higher cloud behind the iridescent cloud. This higher cloud was not visible to the eye and is not to be confused with the very small amounts of cirrus present in the sky but not in the photograph. Apart from the low bank of stratocumulus, the background to the iridescent cloud appeared to be blue sky during the shorter period of the observations when the photograph was taken. A deep red filter was used. Small horizontal ripples in the cloud structure were plainly visible when the colours had almost disappeared.

A. WALTERS.

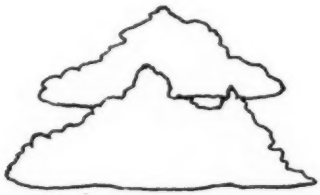
[On November 24, 1948, the height of the freezing level over Aldergrove was about 11,000 ft. and the temperature at 20,000 ft. was about −9°F.—Ed. *M.M.*]

NOTES AND NEWS

Rapid cumulus development at Dishforth

Mr. P. S. Griffiths of Dishforth has recorded the following notes on the rapid cumulus development at Dishforth on June 28, 1949. At 1400 G.M.T. an anticyclone was situated to the west of the Hebrides with a slack north-easterly gradient over north-east England and a weak occlusion, from west of Norway to the Scottish border, was moving slowly south-east. The airstream ahead was moist and rather unstable between 7,000 and 14,000 ft.

Small cumulus at midday, was observed to be developing rapidly over the whole sky by 1400 when the photograph facing p. 357 was taken. The surface temperature by this time had risen to 83°F. The cumulus on the right of the photograph was first observed as a small bubble above the layer



AA whence it developed into that shown in a matter of 20 minutes. Theodolite observations on the ascent of peaks of cloud in three successive minutes showed an ascent of 1° in the first minute, 0·5° in the second and 0·8° in the third. Unfortunately it was not possible to locate exactly the position of the particular cloud but it was estimated at some 12 miles to the north. (This would indicate an ascent of 1,000 ft./min.). This development was not restricted to this particular cloud but similar convection was going on over the whole sky.

Previously the rather unusual occurrence of cumulus cloud developing from two distinct levels had been observed. There was no doubt about this because the tops of the lower cloud were observed rising in front of the base of the higher development as shown in the accompanying sketch. The bases were estimated at 2,500 and 4,500 ft.

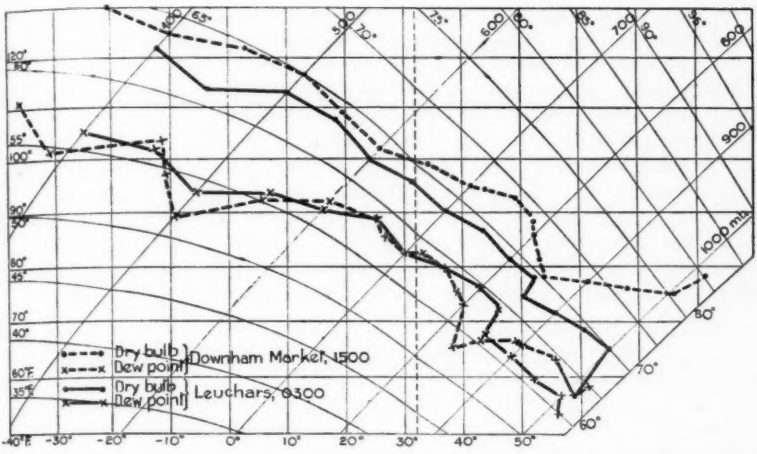


FIG. 1—TEPHIGRAM OF UPPER AIR ASCENTS OVER DOWNHAM MARKET AND LEUCHARS, JUNE 28, 1949

The ascent at Leuchars was made just ahead of the occlusion

[I should call the cloud on the right cumulonimbus which is also visible in the background. A rate of growth of 1,000 ft./min. is large for this country but I should hesitate to call it exceptional. Though simultaneous growth of convectional clouds at different levels is not very rare, I have never seen anything quite like the sketch. The upper layer has generally the character of turret clouds, though the base is not necessarily at medium levels.—C. K. M. Douglas.]

THE WEATHER OF OCTOBER 1949

Mean pressure was above 1020 mb. in the Ukraine and over most of central and southern Europe, except the southern parts of Greece and Italy, and was also above 1020 mb. in Madeira. It was slightly below 1000 mb. south-westward of Iceland. The mean was a few millibars above normal in the region with pressure above 1020 mb. and also over the Mediterranean.

Over the British Isles the weather of October was abnormally warm until the 15th, subsequently very unsettled cooler conditions set in and lasted until the 26th. From the 25th or 26th onwards it was really cold, the weather seeming to change abruptly from summer to winter. The month was excessively wet over a large area including the Thames Valley and southward to the coast and locally in west Scotland. In north-east Scotland and much of north-east England it was drier than usual.

At the beginning of the month an anticyclone initially situated north of the Azores, moved eastward to central Europe. Meanwhile a depression south of Greenland and associated troughs moved east. Fair weather prevailed over the British Isles apart from slight rain in the west and north and considerable mist and fog. Very high temperatures were recorded for the time of year, the highest readings being registered for the most part from the 3rd to 5th. Maxima of 79°F. and 76°F. respectively were recorded at Camden Square on the 3rd and Manchester on the 4th, these readings being records at these places for October since the extremely high readings recorded in October 1921.

On the 6th and 7th a depression centred well out over the Atlantic westward of Ireland moved very slowly east-north-east, while secondary troughs moving east caused rain in the west and north. From the 8th to 10th a shallow trough of low pressure off our south-west coasts moved slowly north-east over the British Isles and was associated with a thundery type of rain which was fairly heavy locally. On the 11th a new deep depression was centred in mid Atlantic; this disturbance moved slowly north-east during the ensuing days reaching the north of Norway by the 14th. On the 11th troughs associated with this depression moved east over the British Isles giving rain generally and thunder locally, but thereafter a ridge extending from an anticyclone over south-west Russia moved north over England, and fair, very warm weather with morning fog prevailed, apart from local rain in Ireland and north-west Scotland.

Subsequently very unsettled and cooler weather set in, with frequent rain and thunderstorms and local gales. On the 17th a small depression moved rapidly across the Atlantic to north-west Ireland, deepening as it moved, and then turned north-north-east to the northern North Sea. Widespread gales occurred in the British Isles on the 18th, while rainfall was general and heavy in places from the 17th to 19th (2·74 in. at Keswick and 2·13 in. at Stronachlacher, Stirling, on the 17th). During the next few days an unstable maritime polar air-stream covered the country causing thunderstorms and heavy showers locally (3·41 in. fell at Balcombe Water Works, Sussex, and 2·73 in at Patcham Farm on the 20th). On the 23rd a small depression off our south-west coasts moved rapidly across England to the North Sea and thence to the Baltic and on the 25th and 26th another deep depression crossed England to southern Scandinavia. Gales occurred on the 23rd, 25th and 26th, the one on the 23rd causing considerable damage and one death on the south-east coast of England. Rainfall was very heavy during this period, particularly on the 25th when falls of more than 2 in. were widely registered; 2·10 in. was measured at Ashford, Kent, and 2·61 in. at Howick Hall Gardens, Northumberland, on the 23rd, 3·00 in. at Mindrum, Northumberland, 3·15 in. at Donaghadee, Co. Down, 3·50 in. at Peebles, Midcalder, and Mid Lothian and 3·60 in. at Largs, Ayrshire, on the 25th and 2·13 in. at Knockholt, Kent, on the 26th. On the 27th the Azores anticyclone with a ridge extending northwards moved east over the British Isles and thereafter to Germany and maintained fair weather, apart from fog in south-eastern districts, but troughs of low pressure associated with Atlantic depressions caused rain at times in the west and north.

The general character of the weather is shown by the following provisional figures:—

	Air Temperature			Rainfall		Sunshine	
	Highest	Lowest	Difference from average daily mean	Percentage of average	No. of days difference from average	Percentage of average	Percentage of possible duration
	°F.	°F.	°F.	%		%	%
England and Wales ..	79	22	+3·5	155	−1	103	32
Scotland	72	17	+3·1	131	+1	81	22
Northern Ireland ..	69	31	+3·2	139	+3	85	23

RAINFALL OF OCTOBER 1949

Great Britain and Northern Ireland

County	Station	In.	Per cent of Av.	County	Station	In.	Per cent of Av.
London	Camden Square ..	4·83	184	*Glam.*	Cardiff, Penylan ..	8·72	184
Kent	Folkestone, Cherry Gdns.	7·75	192	*Pemb.*	St. Ann's Head	7·17	163
"	Edenbridge, Falconhurst	8·49	236	*Card.*	Aberystwyth	8·67	209
Sussex	Compton, Compton Ho.	9·67	211	*Radnor*	Tyrmynydd	8·09	122
"	Worthing, Beach Ho. Pk.	7·57	209	*Mont.*	Lake Vyrnwy	9·33	155
Hants.	Ventnor, Roy. Nat. Hos.	8·06	205	*Mer.*	Blaenau Festiniog ..	12·48	122
"	Bournemouth	7·61	179	*Carn.*	Llandudno	4·61	137
"	Sherborne St. John ..	7·32	208	*Angl.*	Llanerchymedd ..	7·21	161
Herts.	Royston, Therfield Rec.	4·53	167	*I. Man.*	Douglas, Borough Cem.	6·29	139
Bucks.	Slough, Upton	6·16	220	*Wigtown*	Port William, Monreith	5·26	133
Oxford	Oxford, Radcliffe ..	6·38	221	*Dumf.*	Dumfries, Crichton R.I.	6·39	162
N'hant	Wellingboro', Swanspool	4·32	171	"	Eskdalemuir Obsy. ..	7·51	139
Essex	Shoeburyness	5·29	224	*Roxb.*	Kelso, Floors	4·65	160
Suffolk	Campsea Ashe, High Ho.	3·40	130	*Peebles.*	Stobo Castle	5·38	156
"	Lowestoft Sec. School ..	2·56	92	*Berwick*	Marchmont House ..	5·63	147
"	Bury St. Ed., Westley H.	4·39	162	*E. Loth.*	North Berwick Res. ..	5·16	174
Norfolk	Sandringham Ho. Gdns.	3·93	129	*Midl'n.*	Edinburgh, Blackf'd. H.	4·25	155
Wilts.	Bishops Cannings ..	6·75	203	*Lanark*	Hamilton W. W., T'nhill	4·29	132
Dorset	Creech Grange ..	7·07	139	*Ayr*	Colmonell, Knockdolian	5·65	127
"	Beaminster, East St. ..	7·57	170	"	Glen Afton, Ayr San. ..	7·46	146
Devon	Teignmouth, Den Gdns.	6·51	168	*Bute*	Rothesay, Ardencraig ..	9·10	206
"	Cullompton	5·98	145	*Argyll*	L. Sunart, Glenborrodale	10·33	157
"	Barnstaple, N. Dev. Ath.	7·57	166	"	Poltalloch	6·45	131
"	Okehampton, Uplands	10·41	173	"	Inveraray Castle ..	8·97	127
Cornwall	Bude School House ..	8·17	201	"	Islay, Eallabus	5·49	115
"	Penzance, Morrab Gdns.	8·84	190	"	Tiree	7·47	164
"	St. Austell	9·22	175	*Kinross*	Loch Leven Sluice ..	4·67	136
"	Scilly, Tresco Abbey ..	6·21	163	*Fife*	Leuchars Airfield ..	3·72	143
Glos.	Cirencester	6·56	198	*Perth*	Loch Dhu	12·35	173
Salop	Church Stretton ..	4·41	120	"	Crieff, Strathearn Hyd.	6·31	161
"	Cheswardine Hall ..	3·92	126	"	Pitlochry, Fincastle ..	3·58	110
Staffs.	Malvern, Free Library	5·53	186	*Angus*	Montrose, Sunnyside ..	3·67	133
Worcs.	Birmingham, Edgbaston	5·42	195	*Aberd.*	Braemar	3·23	86
Warwick	Thornton Reservoir ..	5·36	196	"	Dyce, Craibstone ..	3·09	92
Leics.	Boston, Skirbeck ..	4·46	163	"	Fyvie Castle	2·42	63
Lincs.	Skegness, Marine Gdns.	2·87	105	*Moray*	Gordon Castle	1·75	55
"	Mansfield, Carr Bank ..	3·51	115	*Nairn*	Nairn, Achareidh ..	1·81	79
Notts.	Buxton Terrace Slopes	4·67	95	*Inv's*	Loch Ness, Foyers ..	2·77	82
Ches.	Bidston Observatory ..	3·32	102	"	Glenquoich	11·82	118
Lancs.	Manchester, Whit. Park	2·89	88	"	Fort William, Teviot ..	12·15	171
"	Stonyhurst College ..	4·64	103	"	Skye, Duntuilm ..	8·33	153
"	Blackpool	5·69	153	*R. & C.*	Tain, Tarlogie House ..	1·17	43
Yorks.	Wakefield, Clarence Pk.	3·02	105	"	Ullapool	2·32	49
"	Hull, Pearson Park ..	2·18	73	"	Applecross Gardens ..	8·21	138
"	Felixkirk, Mt. St. John	2·39	83	"	Achnashellach	8·18	108
"	York Museum ..	2·24	83	"	Stornoway Airfield ..	4·87	99
"	Scarborough	2·64	84	*Suth.*	Loch More, Achfary ..	7·90	101
"	Middlesbrough	2·40	80	*Caith.*	Wick Airfield	1·15	39
"	Baldersdale, Hury Res.	5·06	127	*Shet.*	Lerwick Observatory ..	4·45	112
Nor'ld	Newcastle, Leazes Pk.	2·18	71	*Ferm.*	Crom Castle	5·19	160
"	Bellingham, High Green	5·04	129	*Armagh*	Armagh Observatory ..	5·08	187
"	Lilburn, Tower Gdns. ..	5·77	156	*Down*	Seaforde	5·97	168
Cumb.	Geltsdale	5·18	139	*Antrim*	Aldergrove Airfield ..	4·99	166
"	Keswick, High Hill ..	8·87	158	"	Ballymena, Harryville	5·36	145
"	Ravenglass, The Grove	5·14	119	*Lon.*	Garvagh, Moneydig ..	5·64	160
Mon.	Abergavenny, Larchfield	8·71	208	"	Londonderry, Creggan	5·84	159
Glam.	Ystalyfera, Wern House	10·01	145	*Tyrone*	Omagh, Edenfel ..	4·62	126

CLIMATOLOGICAL TABLE FOR THE BRITISH COMMONWEALTH, JUNE 1949

Stations	Pressure		Temperatures							Relative humidity	Mean cloud amount	Precipitation			Bright Sunshine	
			Absolute		Mean values											
	Mean of day M.S.L.	Diff. from normal	Max.	Min.	Max.	Min.	½ Max. and Min.	Diff. from normal	Wet bulb			Total	Diff. from normal	Days	Daily mean	Percentage of possible
	mb.	mb.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	%	oktas	in.	in.		hr.	%
London, Kew Observatory	1020·4	+3·6	84	43	70·3	52·5	61·4	+1·9	55·0	69	5·0	0·50	−1·65	3	7·8	48
Gibraltar	1016·7	−0·6	84	58	79·6	63·8	71·7	+1·2	66·7	73	2·6	0·06	—	3	11·4	79
Malta	1016·2	+1·0	87	61	80·3	65·2	72·7	0·0	67·7	62	2·4	0·04	—	2	12·1	84
St. Helena	1018·2	−0·7	69	54	65·0	55·9	60·5	+0·2	56·4	95	7·3	4·79	+2·06	21	—	—
Lungi, Sierra Leone	1013·2	—	89	69	86·0	74·2	80·1	—	75·6	87	6·1	8·79	—	19	6·2	48
Lagos, Nigeria ..	1013·3	+0·9	90	67	84·6	70·4	77·5	−2·0	75·9	87	7·0	11·59	—	20	4·7	38
Kaduna, Nigeria ..	1010·2	—	92	63	85·5	67·9	76·7	0·0	70·9	77	6·6	8·08	+0·99	21	7·2	57
Chileka, Nyasaland	1023·0	+0·2	81	52	73·9	56·3	65·1	+0·1	57·9	70	3·1	0·08	−0·05	3	7·1	63
Lusaka, Rhodesia ..	1020·8	+0·3	79	45	74·8	50·7	62·7	+1·2	52·9	69	2·5	0·00	−0·05	0	8·7	78
Salisbury, Rhodesia	1023·8	+0·2	74	39	69·0	44·1	56·5	−0·7	48·6	69	2·4	0·00	−0·09	0	7·9	71
Cape Town	1020·6	+0·5	85	38	71·3	49·1	60·2	+4·5	48·6	67	3·7	2·57	−1·93	10	—	—
Palmie fontein, S. Africa	1029·6	—	71	25	64·4	35·4	49·9	—	39·3	77	2·0	0·28	—	3	8·0	—
Mauritius																
Calcutta, Alipore Obsy.	999·3	0·0	102	74	93·8	79·4	86·5	+1·5	81·8	77	5·2	8·93	−2·98	17	5·7	42
Bombay	1004·0	0·0	91	75	88·2	78·5	83·3	−0·7	78·1	84	5·9	18·31	−1·56	24	4·9	37
Madras	1004·1	+0·3	101	73	95·9	78·9	87·4	−2·6	76·1	66	5·6	3·99	+2·02	13	8·0	62
Colombo, Ceylon ..	1009·1	+0·5	89	73	85·3	76·8	81·1	−0·5	76·3	83	6·4	12·46	+5·14	25	5·1	41
Singapore	1009·4	+0·5	92	71	87·2	76·5	81·9	+0·4	77·3	81	5·6	7·83	+0·96	16	5·3	43
Hongkong	1005·0	−0·8	91	74	85·9	79·2	82·5	+1·1	78·1	84	—	21·40	+5·70	19	3·7	27
Sydney, N.S.W. ..	1018·5	+0·6	67	39	59·9	47·5	53·7	−1·0	48·6	84	4·8	16·66	+11·92	17	4·1	42
Melbourne	—	—	59	32	53·4	41·6	47·5	−2·9	44·1	83	5·6	2·06	0·00	15	2·6	27
Adelaide	1024·5	+5·1	68	37	58·6	43·8	51·2	−2·4	46·1	71	5·0	1·22	−1·86	11	4·7	48
Perth, W. Australia	1019·9	+1·9	77	44	68·9	50·7	59·8	+3·0	54·4	67	4·0	3·90	−3·04	14	5·7	57
Coolgardie	1023·0	+4·1	74	36	64·5	43·3	53·9	+1·1	47·7	68	3·1	0·38	−0·88	6	—	—
Brisbane	1017·9	−0·4	73	39	66·9	49·5	58·2	−2·0	51·9	63	2·9	2·85	+0·06	9	7·7	73
Hobart, Tasmania	1021·7	+7·4	63	30	51·9	38·3	45·1	−1·9	40·1	78	5·4	1·06	−1·17	10	4·1	45
Wellington, N.Z. ..	1010·8	−3·4	64	36	53·1	43·0	48·1	+0·1	45·8	89	5·5	5·83	+1·06	19	3·5	38
Suva, Fiji	1014·3	+0·7	86	68	81·5	71·5	76·5	+1·8	72·7	83	5·8	3·74	−2·97	17	5·5	50
Apia, Samoa ..	1011·9	+0·6	87	68	86·0	73·3	79·7	+1·0	75·9	79	4·1	3·47	−1·51	14	8·5	75
Kingston, Jamaica	1014·5	+0·7	93	71	88·8	74·3	81·5	+0·2	74·9	73	4·0	1·13	−2·97	4	7·4	56
Grenada, W. Indies	—	—	89	71	84·0	74·0	79·0	0·0	75·0	82	4·0	9·31	+1·06	22	—	—
Toronto	1015·2	+0·5	94	39	82·9	61·2	72·1	+8·3	59·9	71	4·8	0·06	−2·60	3	10·4	67
Winnipeg	1010·0	−1·8	97	30	75·5	51·3	63·4	+1·1	52·8	84	6·4	2·71	−0·40	12	8·9	55
St. John, N.B. ..	1016·0	+2·5	74	42	65·0	49·8	57·4	+0·9	53·0	78	7·1	1·93	−1·34	8	7·6	48
Victoria, B.C. ..	1018·0	+1·2	80	42	66·7	47·5	57·1	+0·1	47·8	66	6·2	1·15	+0·31	7	10·5	66

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